Award Number: 05HQGR0060

# CURRENT UPLIFT RATES IN THE SAN GABRIEL MOUNTAINS

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# CURRENT UPLIFT RATES IN THE SAN GABRIEL MOUNTAINS

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**Abstract**

This grant supported the installation and initial survey of geodetic markers in the San Gabriel Mountains, with the long-term goal of determining uplift rates from future surveys. Because of permitting and access restrictions, we were able to make the installations and surveys in only a few areas, though these include some of the regions of highest average topography. We installed twelve Class-A vertical benchmarks along Highway 39, in four clusters of three marks each, and performed two GPS surveys of each cluster. We also surveyed four points in a cluster on Kratka Ridge, one of the few locations with good bedrock outcrops; in order to avoid permitting issues, these surveys were made to temporary markers which were located relative to the rock surface using close-range photogrammetry. This method of ‘‘no-trace’’ monumentation could be used in other areas with permitting restrictions, and also provides a ground reference which is not a target for vandalism.

## Report

## 1. Introduction

Part of understanding the seismic hazard in the Los Angeles area requires improved understanding of its most noticeable topographic feature: the San Gabriel mountains, which rise abruptly at the north end of the Los Angeles basin. We proposed to begin survey-mode GPS measurements in this area, in order to establish rates of deformation, particularly in the vertical, to help constrain models of faulting in this area. Given the investments in continuous GPS, using survey-mode GPS, with occasional brief measurements, might seem unnecessary, but few continuous GPS stations have been built in the San Gabriel Mountains, largely because of permitting problems; because of low coherence from vegetation changes, InSAR data has not been useful. **Figure 1** shows the locations of continuous GPS stations from SCIGN (magenta triangles) and PBO (cyan triangles). The low station density in the San Gabriels is clear, as is the reason: it is difficult to permit continuous GPS sites inside the Angeles National Forest (light green) and impossible to do so inside Wilderness Areas (dark green).

We believed that survey-mode measurements, with their much lower impact, had a better chance of being possible in this region, and proposed to make these measurements in ways that would mitigate monument noise and setup error. We proposed to make initial measurements and archive the data; the long-term plan is that later measurements, and the final analysis, would be made by us or by other groups, depending on opportunities and funding.

This work was initially funded in 2005, but was delayed to allow for recovery from the signal (and road damage) caused by the heavy rainfall of 2004/2005, and also so that we could see where PBO would be installing GPS stations in this area. The PBO locations were established by late 2007, at which time we began reconnaissance for sites, and developed a plan (described below) for measurements in three areas, all of which required permits from the US Forest Service, and one of which also needed an encroachment permit from the California Department of Transportation (Caltrans). We applied for these in early 2008, but did not receive them until December of that year, allowing us just enough time to install monuments and make a partial survey before the area was closed by snow (fortunately this was a late

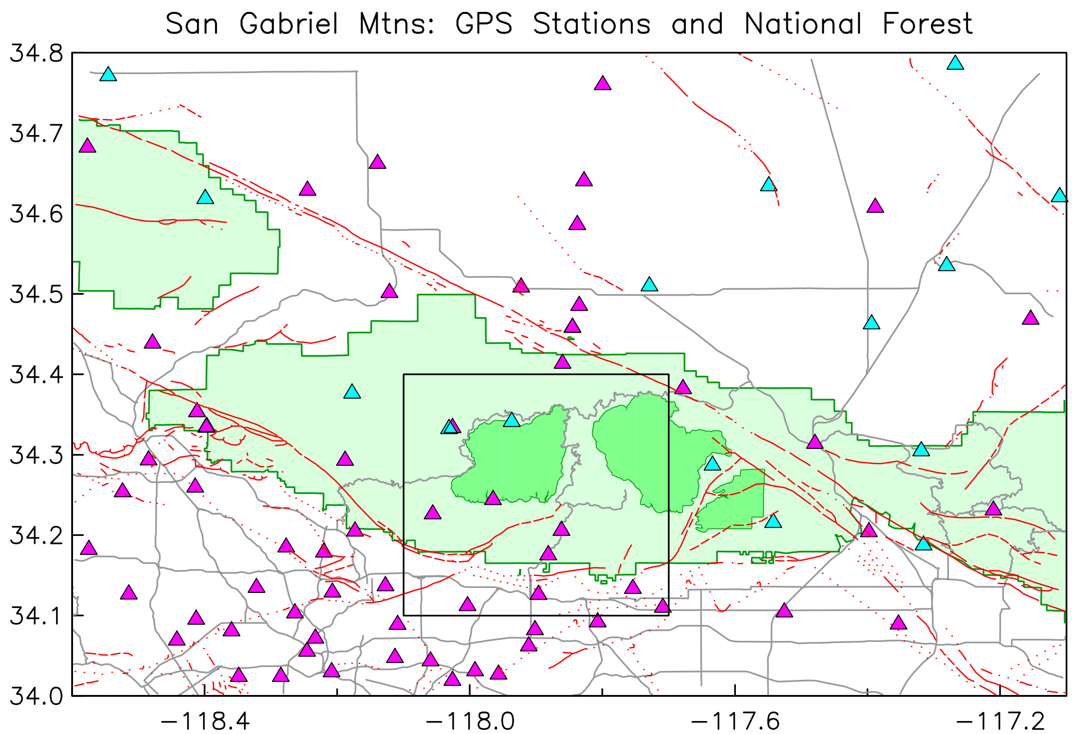


**Figure 1**

winter). To complete the measurements we had to wait until spring of 2009 when access to the sites was again possible.

## 2. Work Plan

To get high accuracy in our estimates of the long-term rates, especially in the vertical, we installed ‘‘monument clusters’’ at each site. So far as we know this method is unique to our group, having been first used by us for surveys around the Rose Canyon fault. The goal is partly to decrease error from monument noise. The best (though costly) way to reduce the effects of near-surface instabilities is to build, as SCIGN and PBO have, deep-braced monuments; as a cheaper alternative, for survey-mode measurements, we use multiple monuments at each site. If the individual monuments of a cluster move independently, then averaging the measurements to $N$ monuments will reduce $\sigma_{rw}$ by $1/\sqrt{N}$: four monuments will cut the error in half. Using multiple monuments also makes the survey more robust against a particular monument turning out to have large motions and also means that destruction of an individual monument does not mean that the site is lost.

Part of the advantage of this method comes from the ability to measure between monuments to very high precision; this both allows us to detect unstable markers, and also means that we can estimate the noise level without an extensive time series, because the relatively large white-noise and flicker-noise components in GPS time series are absent for short-baseline measurements. Over baselines of 100 meters GPS measurements are free from propagation effects and reference-frame problems.

However, to take advantage of the very high accuracy of GPS over short distances we must be able to reproducibly position an antenna above the actual mark on the ground to sub-millimeter accuracy: something not possible with a tripod and optical plummet. In 1998 we designed a high-precision fixed-height antenna post that is kinematically positioned on the mark (see **Figure 8** below for an example).

Using a fixed-height system automatically reduces setup error in the vertical. The antenna post is a large-diameter precision-ground stainless steel rod. This is held in place by three adjustable chains which attach to a spring-loaded collar on the post—this introduces elasticity into the setup so that slight variations in force cannot induce permanent deformation. The post is set vertically using turnbuckles to adjust the length of each chain; once this is done the turnbuckles are locked in place. The hold-down chains are attached to the ground at three points, each about two feet away from the central mark

Most fixed-height antenna mounts use levels permanently attached to the mount; but these will be affected by any bending of the post. We instead use a separate leveling system, with very sensitive bubble levels. This is clamped to the post during setup, and can be rotated around the post to verify verticality and check its own calibration (by rotating it through 180°). This style of setup is, at first, more challenging than one using a tripod, but after some training it can be done as easily—and almost 10 times more accurately. In tests in our lab (using a micrometer mounted on a milling machine as a check) we find that different people can independently set up this equipment to better than 0.1 mm repeatability.

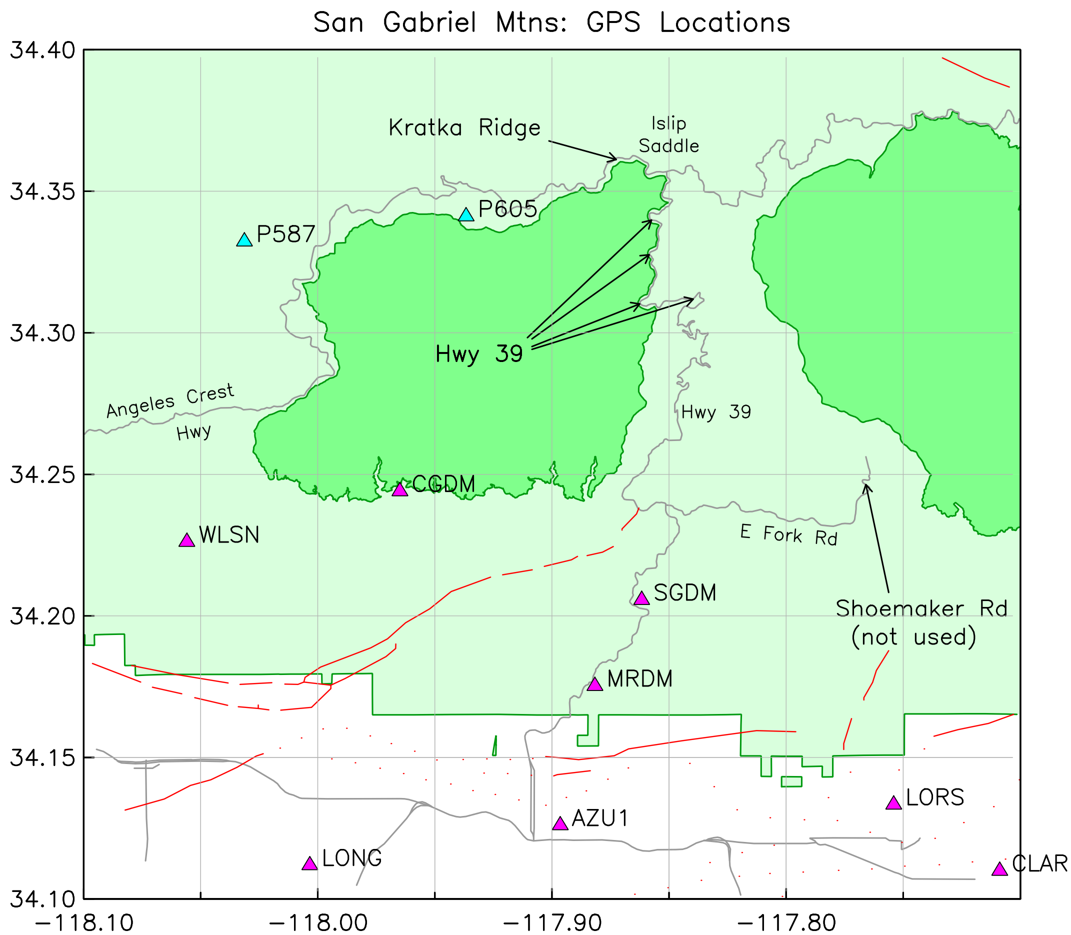


**Figure 2**

## 2.1. Site Selection and Permitting

Our primary goal was to find sites along one of the original SCIGN profiles, which ran NS across the San Gabriels at about −117.9°. **Figure 1** shows the gap in the profile across the mountains. We expected permitting to be easier than it was for SCIGN because of the minimal impact of our setup:

except when observing, only the surface marks would be visible. We sought four attributes for sites:

- Relatively stable material, such as rock outcrops, large boulders, or massive concrete structures.
- Ease of access, through proximity to a road on which vehicles are allowed.
- Sky view: a challenge given trees on ridge tops, narrow canyons, and steep slopes between.
- Some security, ideally such that equipment can be left overnight with reasonable safety.

The first result of searches for sites was to establish that surface outcrops of good rock are rare in the area we were interested in. We were able to identify several possible locations, which are shown on **Figure 2**. These came in three groups:

1. Along Shoemaker Canyon Road; this is an unpaved road (generally known as the ‘‘Road to Nowhere’’ that was constructed in the 1950’s partway along the side of the canyon of the East Fork of the San Gabriel River; construction was abandoned, but the road remains, formally, a county road. The unpaved portion has gated access for firefighting, but usually has only foot access. We found several places at which marks could be in relatively good rock by setting them in the roadbed that is in a roadcut—though with some care to see as much sky as possible. We planned to recess the marks far enough that they would be safe from the periodic grading that this road undergoes.
2. Along the section of Highway 39 between Islip Saddle and Crystal Lake. This was constructed in the 1960’s, but because of frequent slides and high maintenance costs was closed for public use in 1978, though Caltrans still maintains it, to lower standards, for access by firefighters, and because returning it to the Forest Service would cost more than maintenance does. At a few locations where the highway crosses a ridge line, it was dug back into the ridge far enough to create large turnouts on the outside edge: these provided locations at which marks could be set outside the road, but still in material that was relatively undisturbed from its original state.
3. The easternmost end of Kratka Ridge, near the point where the Pacific Crest Trail crosses Angeles Crest Highway. This was one of the few large outcrops of good rock we found; it also had relatively sparse tree coverage.

In our preliminary discussions with the US Forest Service we indicated that we planned to install 20 pin-type monuments at 20 sites (4 each at Kratka Ridge and Shoemaker Canyon, and 12 along Highway 39); each site would involve drilling, into bedrock outcrops, four 2″ diameter holes 6″ deep: one for the main mark and three for the hold-downs. Despite the very small area involved (a total of 5.2 square feet), the number of holes (and possibly the word ‘‘drilling’’) led to a response that we would need to do a full environmental impact assessment (including biological and archaeological surveys); permit approval, if granted, would take at least a year to get and would cost about $10,000 in Forest Service fees.

### 2.2. Site Construction: Highway 39

Given this setback, we revised the type of monuments to be installed, and the sites to be used. Instead of using pins set in shallow holes in hard exposed bedrock, we went to deeper marks set in drilled holes: essentially a version of the ‘‘Class A’’ rod mark designed by the National Geodetic Survey (Floyd 1978). While this design was more expensive, to fabricate and to install, it could be put in less solid material, which allowed us to install the marks inside the Caltrans easement (though off the road); given that this area was already seriously disturbed, the Forest Service was willing, though reluctant, to provide us with a Special-Use Permit. While working within the Caltrans easement also required us to obtain a Caltrans encroachment permit, this was possible, though quite time-consuming. **Figure 4** through **Figure 7** show site plans for the four locations chosen, including the Highway 39 surface and the Caltrans easement (dashed lines).

**Figure 3**: Photographs of the monuments used on the Highway 39 profiles. Left, the monument: a cap with a machined divot welded to a 6.5′ pipe. Center, the monument as installed, at a site without asphalt at the surface. Right, the monument covered with a vinyl cap, at a site with asphalt present.

The monuments installed had specially-machined 2″ disks with a conical indentation for the reference point; these caps were welded to Schedule 80 stainless-steel pipe (1.625″ outside diameter) 6′8″ long; after the welding, these pipes were filled with grout in the lab to add stiffness.

For the actual installation, the holes were drilled by Pacific Drilling, a San Diego company that had installed monuments for the PBO. They used a Marl Technologies M5 drill, a truck-mounted hammer rig with a 5″ bit; this turned out to be an excellent choice, since any other drill type would not have been able to penetrate the subsurface material (solid rock in some cases, rubble in others). The rest of the installation was done by members of our group: Frank Wyatt, Don Elliott, Frank Cheng, and Billy Hatfield. The cover photograph shows the drill rig and our equipment, including a mixer for grout. Fortunately water was available from a temporary catchment tank that a Caltrans contractor had set up nearby.

Each hole was drilled to approximately 8′ so that the pipe and mark would end up below grade; the pipe was then inserted and grouted in place by pouring grout around it until the top of the grout came to about 18″ below the mark. The remaining volume was then filled with sand up to the level of the mark, on which a vinyl cap was placed for protection. The remainder of the hole was then filled with sand; for marks installed in asphalted turnouts, the last few inches were filled with compacted cold-mix asphalt. In most cases the marks were about 6″ below grade. **Figure 3** shows the marks before and after installation.

**Table 1: Locations of Marks Installed on Highway 39**

| Name | North lat | East long | Height | UTM Easting | UTM Northing |
|---|---|---|---|---|---|
| G38L | 34.311787 | −117.839889 | 1538.822 | 422721.580 | 3797046.475 |
| G38M | 34.311755 | −117.839989 | 1539.278 | 422712.349 | 3797043.003 |
| G38U | 34.311730 | −117.840094 | 1539.705 | 422702.665 | 3797040.310 |
| G39L | 34.310292 | −117.862637 | 1658.851 | 420627.066 | 3796898.228 |
| G39M | 34.310372 | −117.862684 | 1659.243 | 420622.816 | 3796907.136 |
| G39U | 34.310457 | −117.862720 | 1659.652 | 420619.584 | 3796916.589 |
| G41L | 34.327593 | −117.858526 | 1740.590 | 421021.546 | 3798813.505 |
| G41M | 34.327676 | −117.858569 | 1741.122 | 421017.668 | 3798822.742 |
| G41U | 34.327763 | −117.858595 | 1741.621 | 421015.358 | 3798832.409 |
| G42L | 34.339802 | −117.857630 | 1850.725 | 421115.405 | 3800166.648 |
| G42M | 34.339838 | −117.857730 | 1851.122 | 421106.240 | 3800170.717 |
| G42U | 34.339882 | −117.857824 | 1851.589 | 421097.635 | 3800175.669 |

UTM coordinates are for Zone 11.

**Table 2: Drilling Notes for Marks Installed on Highway 39**

| Name | Hole Depth | Monument Length | Depth of Grout | Asphalt Depth | Notes |
|---|---|---|---|---|---|
| G38L | 3-4′ | 3′ | 20″ | 3″ | Hole in soft material; largely collapsed after drilling. |
| G38M | 4′ | * | 18″ | 3″ | Not much coming out until 6′, except for some large cobbles; last 1½′ in rock, but hole collapsed with large cobbles blocking hole. Lots of grout needed. |
| G38U | 6′ | * | 21″ | 3″ | Mostly soft material (not much hammering of bit), though lots of spoils came up. |
| G39L | 6′ | 5½′ | 18″ | 3″ | May have hit rock at 3′, but mostly in softer material. Hole required large amounts of grout. |
| G39M | 7½′ | 6′ | * | 3″ | At 4′ into good (though sorted) material. |
| G39U | 6′ | 5½′ | * | 3″ | Not many spoils coming to surface: mostly in softer material. |
| G41L | 8′ | 6′ | 26″ | 3″ | In rock: drilling produced only sub-mm chips and powder. |
| G41M | 8′ | 6′ | 22″ | 3″ | In rock. |
| G41U | 8′ | 6′ | 23″ | 3″ | In rock: tough material right below the asphalt. |
| G42U | 6.8′ | 5½′ | * | — | First hole drilled; total depth 8′. First 3′ soft (hammer not going). Caving of granular material decreased depth. |
| G42M | 8′ | 6′ | * | — | Drilling dusty: in good material. |
| G42L | 8′ | 6′ | * | — | Good material, though not as good as at the 41 turnout. |

*Not recorded in field notes.

All drilling and preliminary grouting was done in one (very long) day on December 3, 2008, with the following day devoted to additional grouting, and also to installing a triplet of driven rods around each mark, to be used as the anchoring points for the tension lines used with the antenna supports. For these last we used a rotary hammer to drill to 30″, and then drove 26″ rods to 4″ below the surface.

When drilling the main marks we had several guides to what the subsurface material was like. The hammer on the drill only operates if there is sufficient resistance: in very soft material the drill string can be pushed in without the hammer operating. How much the hole caved after being drilled to its full depth (8′) was also indicative of the consolidation of the material it was drilled in. In a number of cases the hole ended up shallower than expected, forcing us to shorten the marks. This, by itself, is not a source of instability: even for a deeply set Class A mark, horizontal motions at the top are driven by near-surface materials, and not constrained by those at depth. A final source of information on the material was the amount of grout needed to reach the level aimed at (about 18″ below the mark, so as to decouple the top part from shallow soil motion). Some marks required significantly more grout than expected based on the hole size, suggesting some degree of void space in the subsurface material.

Table 1 gives the positions of the marks as determined from subsequent GPS surveys, while Table 2 summarizes the drilling notes for each installation. The mark names use 2 digits for the cluster location (in post miles along Highway 39), followed by an L, M, or U for the lower, middle, and upper mark in each cluster. The order is given from lowest to highest, the reverse of the order in which the marks were drilled.

The “38” cluster may be in sorted spoils; although the bench at this location is quite broad, the cut opposite to it shows heavily weathered material down as far as 50′ to 70′. The material at the “39”

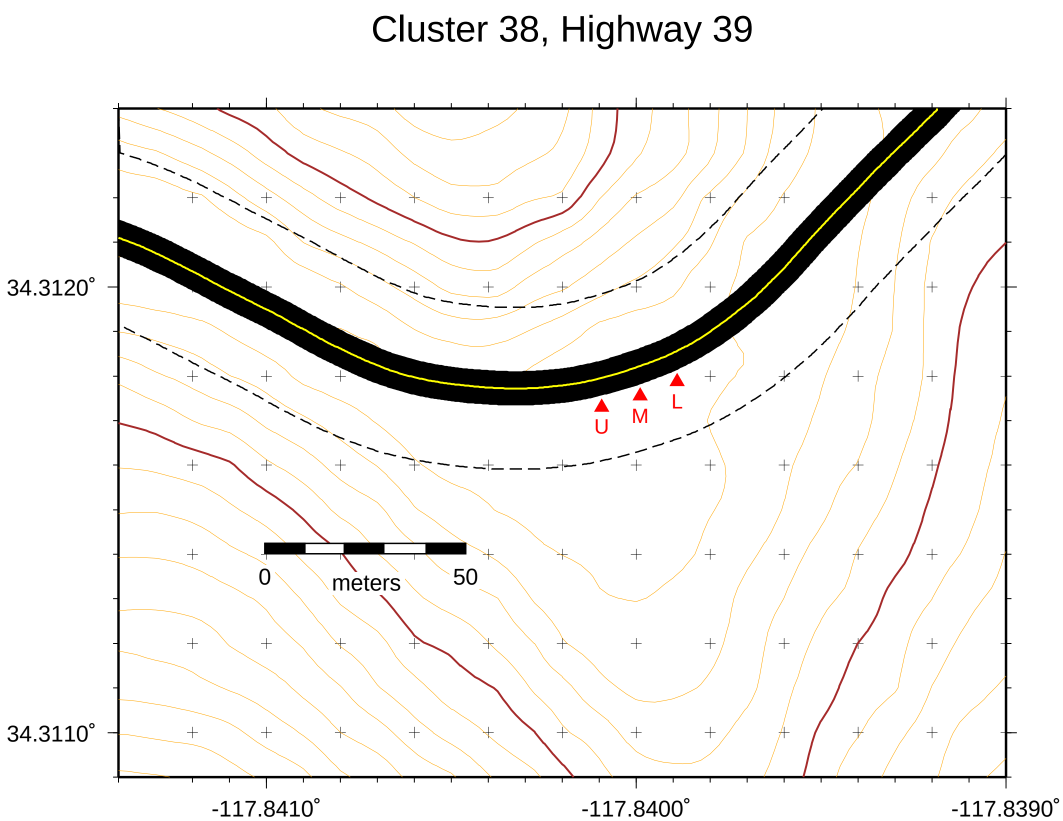


**Figure 4**

cluster was slightly better than this. Both of the two northerly clusters seem to be in much better materials; the "41" holes, in particular, required hammer drilling from the surface to their full depth, and showed little if any caving; we are fairly confident that these are set in competent rock.

**Table 3: Start Times of GPS Data Collection, Highway 39 Arrays**

| G38L | G38M | G38U | G39L | G39M | G39U | G41L | G41M | G41U | G42L | G42M | G42U |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 346.65 | 346.68 | 346.69 | | | | | | |
| | | | | | | | | | 347.65 | 347.67 | 347.68 |
| 21.74 | 21.81 | 21.73 | | | | 21.67 | 21.68 | 21.66 | | | |
| | | | | 111.70 | 111.70 | | | | 111.63 | 111.64 | 111.65 |
| | 112.79 | 112.78 | | | | 112.72 | 112.74 | 112.75 | | | |

**Table 4: Durations of GPS Data Collection, Highway 39 Arrays**

| G38L | G38M | G38U | G39L | G39M | G39U | G41L | G41M | G41U | G42L | G42M | G42U |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 11.43 | 11.08 | 10.98 | | | | | | |
| | | | | | | | | | 8.48 | 8.18 | 8.07 |
| 1.35 | 5.68 | 7.57 | | | | 10.00 | 9.65 | 9.97 | | | |
| | | | | 26.28 | 25.83 | | | | 26.15 | 26.22 | 24.73 |
| | 23.08 | 23.02 | | | | 25.47 | 25.52 | 25.50 | | | |

Cluster 39, Highway 39

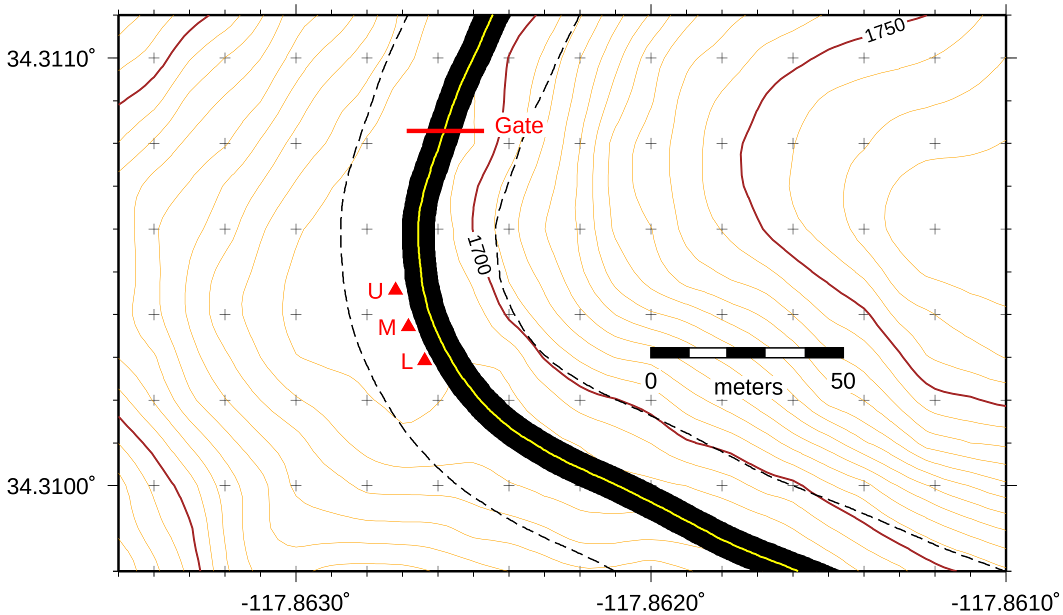


**Figure 5**

Cluster 41, Highway 39

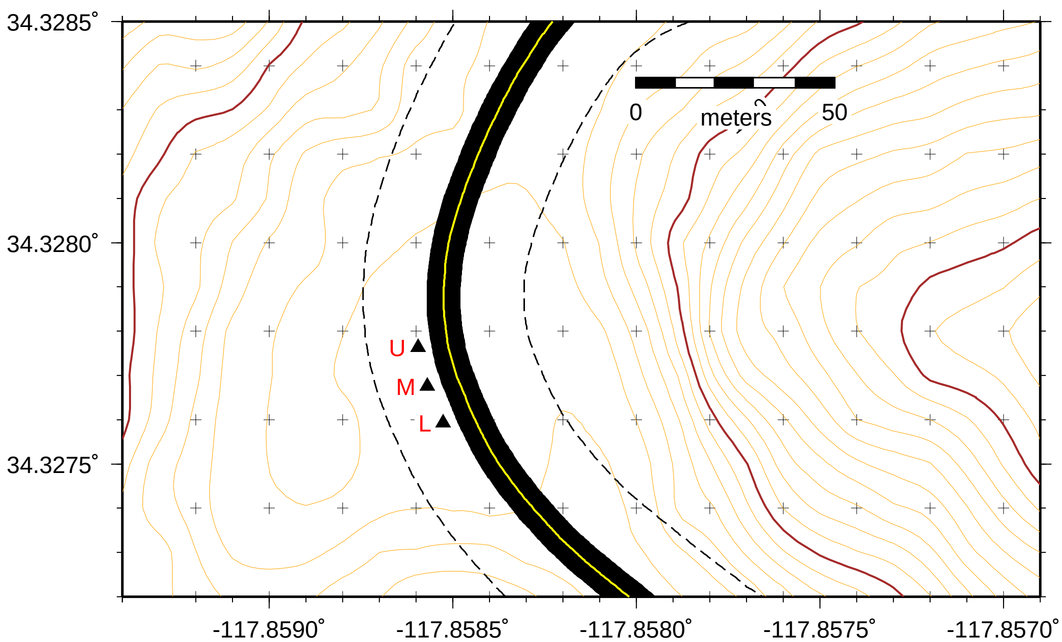


**Figure 6**

## 2.3. Site Surveys: Highway 39

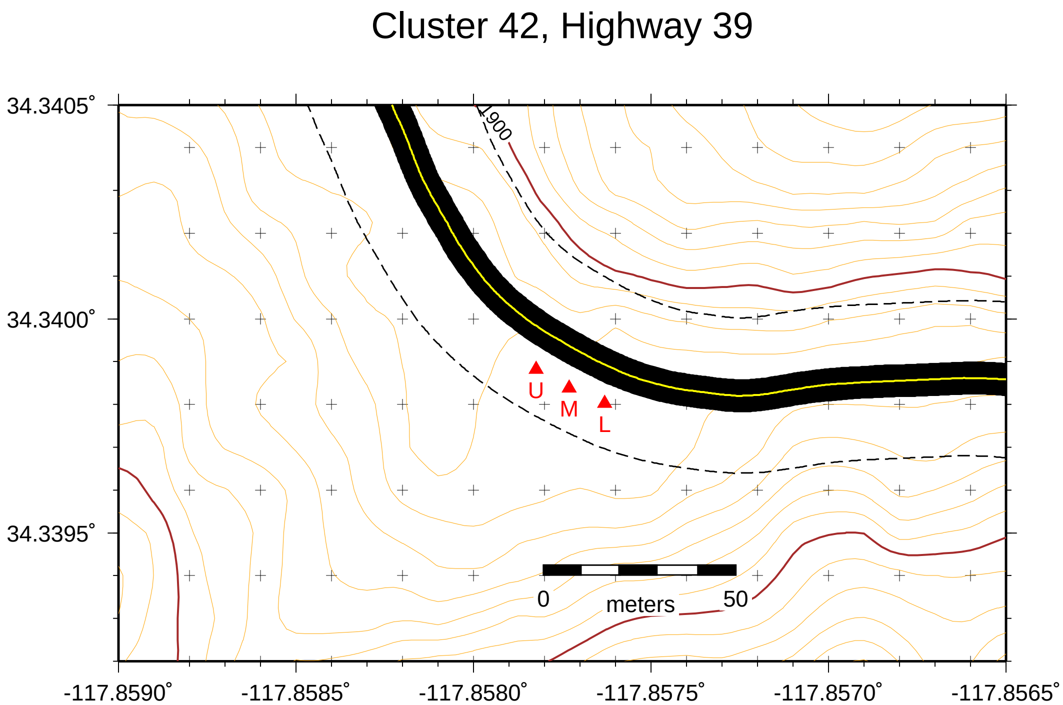


**Figure 7**

We began GPS surveys at the sites along Highway 39 as soon as possible after the marks were installed. All surveys were done with our Ashtech Z-XII3 receivers and choke-right antennas, and using our fixed-height antenna mounts. **Figure 8** shows the equipment used at one setup, while **Figure 9** shows the survey in progress at two of the clusters. The first trip combined survey work with some additional work that was not possible in the rather crowded day of drilling. The two-man crew (Don Elliott and Billy Hatfield) left San Diego late on 2008:345, to allow for two full days of work at the sites. This included surveying at the ''39'' cluster (day 346) and the ''42'' cluster (day 347). In addition, at each mark a 2″ vinyl cap were put for protection; then the holes were backfilled holes with sand to 3″ below the surface; the last 3″ was filled with cold asphalt patch which was tamped until fairly solid, and a plastic survey ''tail'' was buried in the asphalt to aid future mark recovery. Tables 3 and 4 give information on the surveys on both days,

Unfortunately, the end-of-year holidays and access issues (lack of a key) meant that the remaining marks could not be surveyed as promptly. Very fortunately the winter snows held off long enough for the survey to be completed on 2009:021, by Frank Cheng and Billy Hatfield. In this case we were limited by the number of receivers and mounts available, so at the ''38'' cluster we collected data at one site (G38L) only briefly before moving the equipment to a different mark.

In order to check these surveys for possible blunders, and provide a good baseline for future remeasurements, we made a third survey on 2009:111-112. In this case the observers (Don Elliot and Billy Hatfield) camped overnight to allow longer periods of data collection; while the road is closed to public access[1], there are enough vehicles passing that we did not want to risk the equipment by leaving it

[1] Starting at post mile 39.96 (gate shown in **Figure 5**), the road has been closed to public access since 1978, and will probably never be reopened. Because of flood damage in early 2005, the road was closed to public access beyond post mile 32.3; parts of this section still require considerable restoration work. During the period of our survey the road was closed beyond post mile 29. At the time of writing (September 2010) the road is closed starting at post mile 27.

unattended. Again, because of the number of receivers available, two of the marks with the least-good foundations (G38L and G39L) were not surveyed.

**Table 5: Inter-monument Distances: Highway 39 Clusters**

| From | To | Date | North | | East | | Up | | Distance | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Val | $\sigma$ | Val | $\sigma$ | Val | $\sigma$ | Val | $\sigma$ |
| G38L | G38M | 2009:021 | −3647.8 | 1.0 | −9195.1 | 0.9 | 455.9 | 2.8 | 9902.7 | 0.8 |
| G38M | G38U | 2009:021 | −2735.0 | 0.6 | −9662.4 | 0.5 | 440.0 | 1.4 | 10051.6 | 0.5 |
| G38M | G38U | 2009:112 | −2734.8 | 0.8 | −9662.1 | 0.6 | 441.2 | 1.7 | 10051.4 | 0.6 |
| G39L | G39M | 2008:346 | 8926.3 | 0.4 | −4346.2 | 0.4 | 387.6 | 0.9 | 9935.7 | 0.3 |
| G39M | G39U | 2008:346 | 9401.4 | 0.4 | −3276.8 | 0.3 | 438.5 | 0.9 | 9965.8 | 0.3 |
| G39M | G39U | 2009:111 | 9401.3 | 0.7 | −3276.7 | 0.5 | 438.0 | 1.5 | 9965.6 | 0.6 |
| G39M | G39U | 2009:112 | 9401.6 | 0.9 | −3276.8 | 0.7 | 439.3 | 2.4 | 9966.0 | 0.9 |
| G41L | G41M | 2009:021 | 9204.3 | 0.7 | −3969.7 | 0.7 | 520.9 | 1.8 | 10037.3 | 0.7 |
| G41L | G41M | 2009:112 | 9204.5 | 0.9 | −3970.9 | 0.7 | 521.8 | 2.1 | 10038.1 | 0.9 |
| G41M | G41U | 2009:021 | 9677.5 | 0.7 | −2382.6 | 0.6 | 511.9 | 1.7 | 9979.7 | 0.7 |
| G41M | G41U | 2009:112 | 9677.8 | 1.0 | −2382.8 | 0.9 | 513.7 | 2.3 | 9980.0 | 1.0 |
| G42L | G42M | 2008:347 | 3998.2 | 0.6 | −9166.6 | 0.2 | 397.7 | 1.6 | 10008.5 | 0.3 |
| G42L | G42M | 2009:111 | 3998.1 | 1.0 | −9156.5 | 0.7 | 376.3 | 2.2 | 9998.4 | 0.8 |
| G42L | G42U | 2008:347 | 8917.2 | 0.6 | −17796.3 | 0.2 | 864.0 | 1.6 | 19924.2 | 0.3 |
| G42L | G42U | 2009:111 | 8917.5 | 0.7 | −17794.3 | 0.6 | 861.2 | 1.6 | 19922.4 | 0.6 |
| G42M | G42U | 2008:347 | 4919.0 | 0.7 | −8629.8 | 0.2 | 466.3 | 1.6 | 9944.2 | 0.4 |
| G42M | G42U | 2009:111 | 4919.5 | 0.9 | −8637.8 | 0.7 | 484.8 | 2.0 | 9952.3 | 0.8 |

All values from L1/L2 independent processing; units are mm. Errors are formal errors from processing program. Coordinates are in a local Cartesian frame with origin at the first point and vertical along its radius vector.

Table 5 gives the results from these surveys, with the data being processed separately for each cluster. We used the GAMIT software, with the L1 and L2 observables processed independently and then combined, and no zenith delays estimated: this set of processing choices gives the highest precision on baselines this short (10-30 m). This table shows that, with one exception, the measurements made at different times agree at the sub-millimeter level in the horizontal, and to within 1-2 mm in the vertical. The exception is the point G42M, for which the relative distances relative to G42L and G42U differ significantly between surveys. Since the distances from G42L to G42U do not differ, the problem must lie with this one point, though until further surveys are made it will not be possible to see which of the two existing surveys is problematic.

### 2.4. No-Trace Monumentation Using Photogrammetry

As noted previously, the east end of Kratka Ridge provided the best GPS site we found in the San Gabriel Mountains: outcrops of good rock, few obstructions from trees (see the panorama in **Figure 10**) and easy access (just off Angeles Crest Highway). Part of that easy access comes from the Pacific Crest Trail running through this area, but this has a negative side as well: we judged that it would be much more difficult to obtain a Special-Use Permit from the Forest Service to make any alterations in an area that is well-traveled but otherwise unaltered.

In order to make measurements in this location we therefore developed what might be called, after a common backpacker's motto, a ‘‘leave-no-trace’’ system of monumentation: something that would allow precise recovery of the location of different measurements relative to the ground, without any alteration of the natural surface. A method that can do this is not only usable in sensitive areas (such as Wilderness regions), but also minimizes the risk of a monument being destroyed, whether through vandalism or deliberate removal for sale.

**Figure 8**

**Figure 9**

The basic concept is to center the GPS antenna, in the usual fashion (with a tripod and optical plummet) over a mark that is glued to the rock only while surveying. The location of this mark relative to the rock surface is found by photographing both at the time of the survey, and then using photogrammetric methods to create a digital model of the rock surface relative to the center point of the temporary mark.

A later occupation of the same point would repeat this procedure. It would not be necessary for the temporary mark to be in the same location on each occasion; its relative location at each occupation, and hence the relative location of the antenna centered over it, would be found by matching the digital models

**Figure 10**

**Table 6: Locations of Photogrammetric Area on Kratka Ridge**

| Name | North lat | East long | Height | UTM Easting | UTM Northing |
|---|---|---|---|---|---|
| KR2A | 34.361228 | -117.872020 | 2045.120 | 419812.184 | 3802553.828 |
| KR3A | 34.361211 | -117.871924 | 2045.021 | 419820.996 | 3802551.867 |
| KR4A | 34.361247 | -117.871784 | 2042.601 | 419833.904 | 3802555.748 |
| KR6A | 34.361065 | -117.872189 | 2046.101 | 419796.488 | 3802535.886 |

UTM coordinates are for Zone 11.

of the rock surface observed each time. This method does depend on finding rock surfaces that will, bye and large, not change shape significantly between occupations: this will be true if weathering is slight on a timescale of a few years. Examination of the outcrops on Kratka Ridge showed a pattern of lichens that indicates that weathering on these surfaces is slow enough for these organisms to grow and die while still remaining in place: good evidence that the rock surfaces change only slowly.

**Table 7: Intermonument Distances: Kratka Ridge**

| From | To | Date | North | | East | | Up | | Distance | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Val | $\sigma$ | Val | $\sigma$ | Val | $\sigma$ | Val | $\sigma$ |
| KR2A | KR3A | 2009:119 | −1848.2 | 0.6 | 8801.8 | 0.4 | −102.8 | 1.2 | 8994.3 | 0.5 |
| KR2A | KR6A | 2009:119 | −18132.8 | 0.6 | −15505.0 | 0.5 | 969.9 | 1.2 | 23877.7 | 0.5 |
| KR3A | KR3B | 2009:119 | −13.0 | 0.9 | 12.8 | 0.8 | 2.0 | 1.9 | 18.4 | 0.8 |
| KR3A | KR4A | 2009:119 | 3975.5 | 0.5 | 12940.9 | 0.4 | −2418.5 | 1.1 | 13752.1 | 0.4 |
| KR4A | KR4B | 2009:119 | 7.4 | 1.0 | 5.9 | 0.8 | −1.8 | 2.0 | 9.6 | 1.0 |

All values from L1/L2 independent processing; units are mm. Errors are formal errors from processing program. Coordinates are in a local Cartesian frame with origin at the first point and vertical along its radius vector.

Traditionally, photogrammetric methods have involved specialized and expensive calibrated cameras and equally expensive software, aimed at a relatively limited market. Recently, less-expensive photogrammetric software has become available for such purposes as reverse engineering and forensic reconstruction: precisely the kind of close-range work we needed to be able to do. And these systems are designed to work with images collected by high-end consumer digital cameras, which have proven capable of getting images of the quality needed.

In order to test our method, we assembled the following equipment:

1. A digital SLR camera (Canon EOS 40D) costing $\$1,700$.

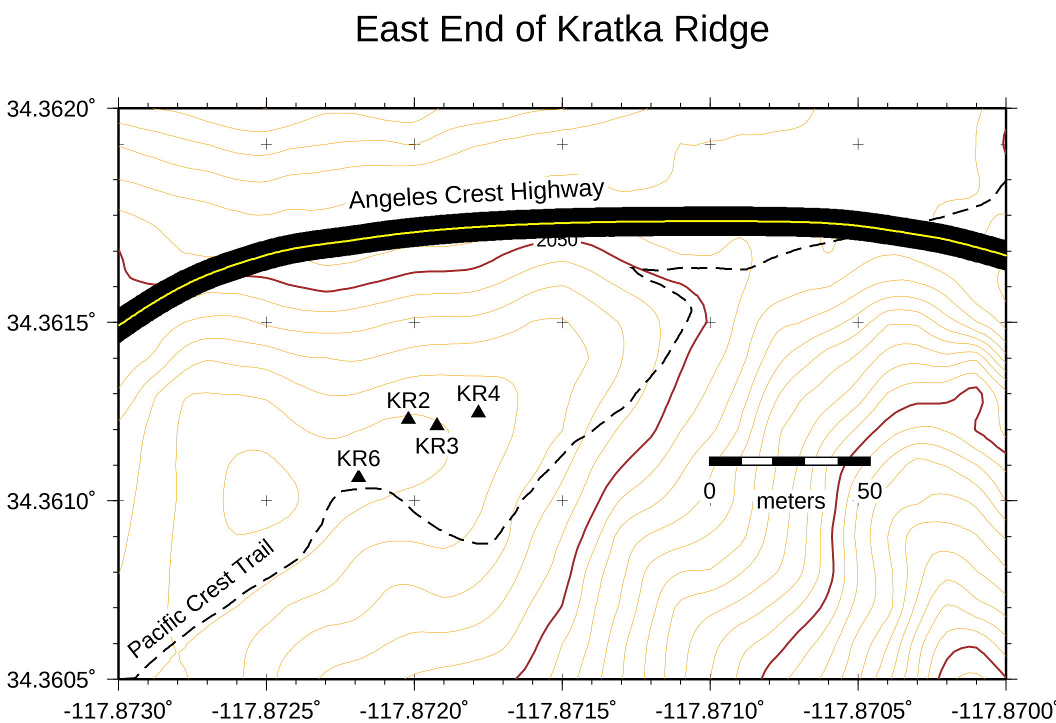


**Figure 11**

2. Photogrammetric software, namely Photomodeler Scanner; this included the option for creating surface models (which requires image matching). With this, the software cost $2,700.

3. Temporary monuments. These were aluminum disks 1.5″ in diameter; on the top, a portion ½″ in diameter was recessed 0.02″, and in the center of this a 90° cone, 0.06″ deep, was milled out to hold the end of the height rods. Except for this center portion, the top of the disk was painted white. After the tripod was centered over the this cone, and the height measured, a disk of black tape on paper, sized to match the diameter and depth of the center recess, was inserted into it; this provided a circular target, which the photogrammetry software could locate to sub-pixel accuracy.

4. Target strips. The software can automatically recognize, locate, and distinguish targets that can be created using the software. Photogrammetry produces a set of coordinates in three dimensions, but with an arbitrary scale, axis orientation, and point of origin. The last can be set to be the center of the temporary monument, but to provide scale and direction (and to strengthen the solution) we constructed ‘‘target strips’’: square metal rods, up to 18″ long with at least eight targets glued on one side. At each location, we set up two long target strips, using clay to support the strips so that each would be level (as determined with a carpenter’s level); the two strips then specify a level plane and establish the direction of the vertical. To orient the final model in azimuth, we used a magnetic compass to find the azimuth of at least one of the strips; as a check on this, we also measured the azimuth of the strip relative to a sighting taken on one of the other setups.

The actual fieldwork was done on 2009:118 and 2009:119. The first day was devoted to choosing the locations for the survey, looking for areas with sound rock, reasonable sky view, and level enough rock to allow setting up a tripod; **Figure 11** shows the four points chosen; one of the best is an outcrop next to the Pacific Crest Trail, a location that would have been unusable for a permanent mark.[2]

[2] At the time of writing (September 2010) the PCT has been rerouted (because of the 2009 Station fire)

**Figure 12**

The sequence followed for monumentation and photogrammetry was:

1. Set up the tripod and move it around to find a location for the center mark that would make it level and use minimal epoxy.
2. Attach the mark with epoxy; it was very efficient to have two people doing the first step while a third followed to do this
3. Set up the target strips around the mark, two of these leveled with clay and level, and one of these set to point to magnetic North.
4. Take photos from several directions, at a fairly high angle, of the setup, using a large sheet to block direct sunlight and avoid shadowing of the surface. In order to image the whole setup the camera needed to be slightly elevated, so most photographs were taken while standing on a step-stool – which on this surface took a second person to brace it, while a third held the shadow screen. We also photographed, without the screen, a block oriented to the direction of the Sun, at well-recorded times, to get an independent estimate of azimuth. Doing this at all four locations took about an hour. **Figure 12** shows a typical setup, at site KR2A.

The time needed for this work meant that the actual survey took place the following day. This included an independent photographic setup at mark KR2A, with the mark itself being left along; at KRA3 and KRA4 the mark was removed, re-attached close by, and an independent GPS and photogrammetric survey made, to simulate what might be expected from a later survey. Given the long survey times needed for the highest GPS precision, there was plenty of time to perform the photogrammetric survey as well. The epoxy worked well: the marks were firmly in place, but came off easily, removing only a small amount of rock.

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to run north from Islip Saddle, so this portion of the trail is not in use except by hikers who access it from Angeles Crest Highway.

Subsequent processing of the GPS data gave the locations of and intersite distances between the marks (Tables 6 and 7); note that there is no direct tie between KR3A and KR3B, or between KR4A and KR4B.

The photogrammetric processing involved, first, solving for the locations of the targets on the strips and on the monument itself; while this made use of prior calibration information collected for this camera, the software also performs a bundle adjustment to solve for positions and camera parameters. Scale was provided by known distances between marks on the strips; orientation was provided by setting two points on each of the two leveled strips to have the same *z* coordinates, and making the *x* axis run along one strip.

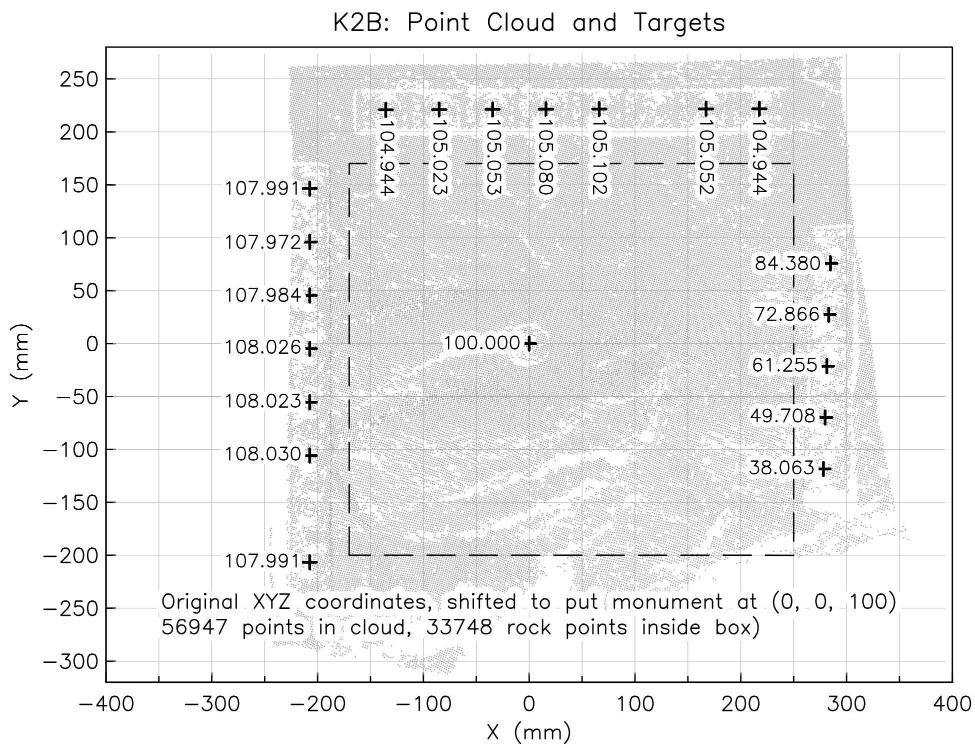


**Figure 13**

After this, the software performed image matching to produce a set of *xyz* coordinates (and *RGB* color values) for as many points as possible: that is, a point cloud that is now familiar from the use of laser scanners. The results of the target positioning and of the point cloud estimate were than saved as text files.

**Figure 13** shows the result, with the locations of the points plotted in gray, and of the targets with crosses. The numbers attached to the targets are the *z* coordinates, where the top of the survey monument has been set to have a value of 100 mm (to avoid negative elevations for the rock surface). The *x* and *y* coordinates of this point have been set to be the origin.

As noted above, two surveys were made at this point, with the mark left fixed; we can use the results from these to evaluate how well we can match the two point clouds. Matching of such clouds, especially when the *xy* coordinate locations, and coverage may differ, is an area of active research. As a first approximation we shifted the points from the second survey to have the same origin as those from the first; we then, for both clouds, took means over 4 mm blocks, used these to construct a surface with 2 mm spacing, and took the difference in $z$ values. **Figure 14** shows contour maps (5 mm contour interval) for the two surfaces over a range of coordinates where both determine the rock surface; clearly these maps are very similar.

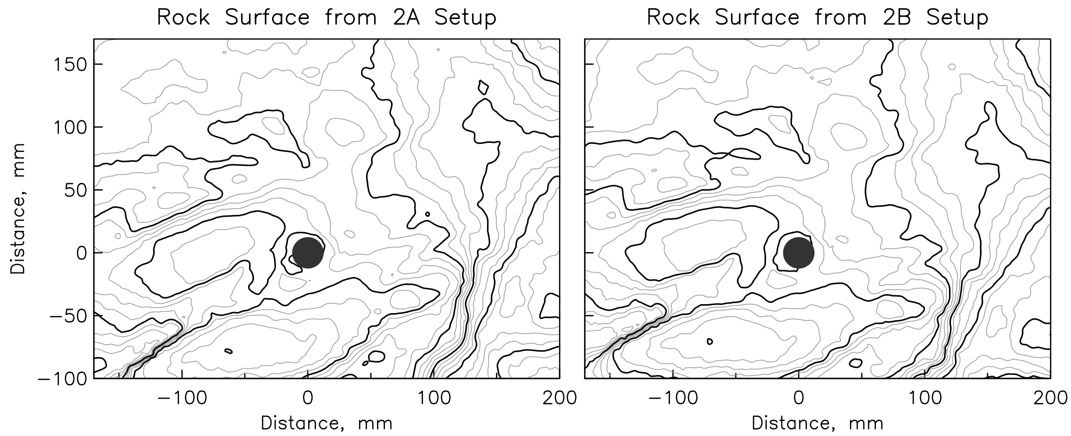


**Figure 14**

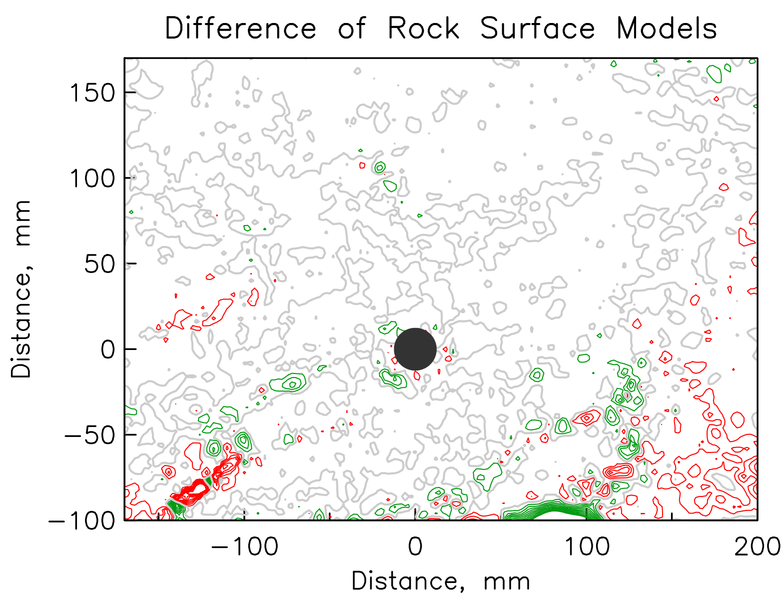


**Figure 15**

Differencing the surfaces shown in **Figure 14** produces, however, substantial disagreements. The reason for this, visible in **Figure 13**, is that one surface is rotated in azimuth relative to the other, something that is not unexpected given the relatively low accuracy of setting the strips to magnetic North. If we rotate the point cloud from the second survey about the $z$ axis, we can obtain a much better fit, shown in **Figure 15**. In this plot the colored contour lines are at a 1 mm interval and the gray contour is at zero. It is however apparent that in areas of high slope there are still significant misfits, probably because in these regions the imaging matching selects different points from the images. If we eliminate the region with $x$ less than -50 and $y$ greater than 100, we obtain the lowest rms misfit for a rotation (of the second dataset) by 6.5° clockwise about the $z$ axis, and the result in **Figure 16**, where we have also shown the distribution of the differences. This rotation, while miminizing the misfit, is slightly biased: the vertical position of the monument is found to have changed by 0.07 mm, when in fact it did not change at all. This level of error is well below the errors in GPS vertical positioning.

**Figure 17** (left frame) shows the misfit and bias as a function of rotation about the *z* axis, and also (center and right frames) as a function of tilt (about the two horizontal axes) and horizontal displacement. The best fit is for a relative tilt very close to 0°, evidence that the leveling procedure used was in fact very accurate. The misfit as a function of horizontal displacement also shows no bias, and the ability to reproduce the location to within better than a millimeter.

Further work with the data collected at the other locations will be needed to fully evaluate this method, but it appears that, at modest cost, it is in fact possible to establish a precise geodetic marker on an irregular surface without physically modifying it: once the survey is complete, the ‘‘monument’’ becomes, effectively, invisible.

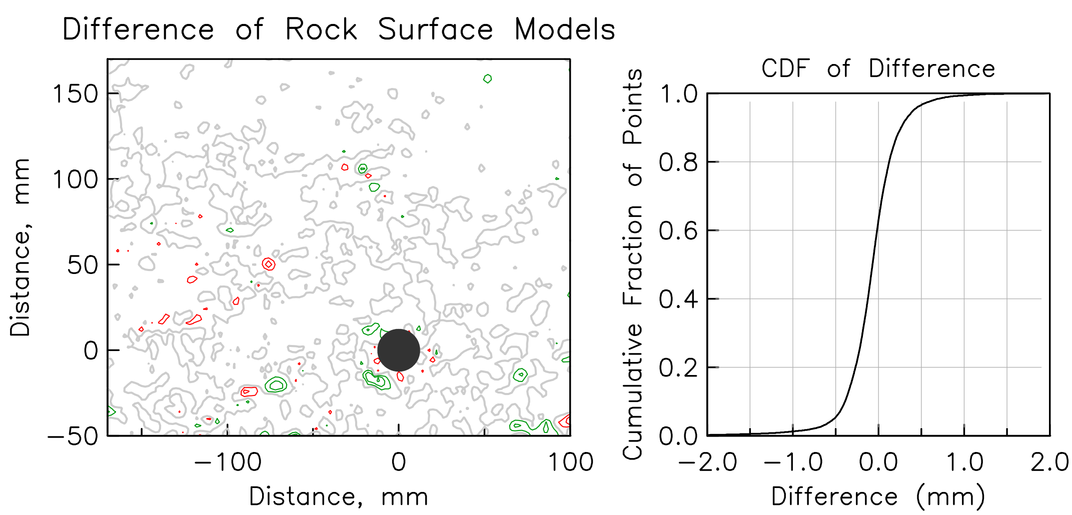


**Figure 16**

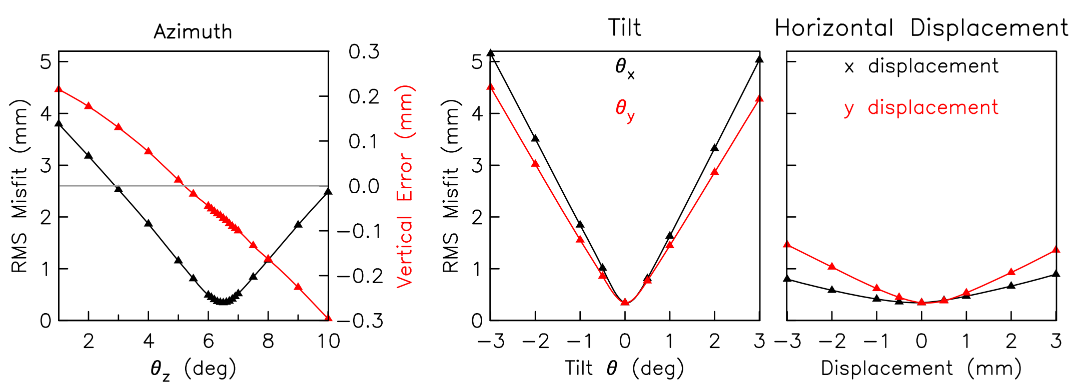


**Figure 17**

## 3. Summary

Permitting restrictions made our final surveys less extensive than we had originally hoped, an outcome somewhat counterbalanced by the success of PBO in establishing several continuous sites in the San Gabriel Mountains. However, we succeeded in establishing an array of well-surveyed points in a part of the San Gabriel mountains that would otherwise be inaccessible to precise geodetic surveys. Our initial surveys have provided redundant high-precision ties between three marks at each of four clusters; the locations of these marks have also been determined precisely relative to continuous GPS sites in the region. What the results will be for motions of these sites will be clear only after time has passed and later repeat surveys have been made. We have archived the GPS data collected at the SCEC Data Center so that it will be available for comparison with subsequent surveys. The photogrammetric point clouds, and the photographs from which they were found, will be stored in a stable location, and will also be provided to the person in charge of USGS geodesy for southern California.

## Reference

Floyd, R. P. (1978). *Geodetic Bench Marks*, Manual NOS NGS 1, U. S. National Ocean Survey.